NASA TECHNICAL MEMORANDUM

A 12-COIL SUPERCONDUCTING "BUMPY TORUS" MAGNET FACILITY FOR PLASMA RESEARCH

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SUMMARY

A retrospective summary is presented of the performance of the two-coil superconducting pilot rig which preceded the NASA Lewis bumpy torus. This pilot rig was operated for 550 experimental runs over a period of 7 years. The long term degradation of certain subsystems of this apparatus have implications for the design of similar facilities. The NASA Lewis bumpy torus facility consists of 12 superconducting coils, each with a 19 cm i.d. and capable of producing magnetic field strengths of 3.0 teslas on their axes. The magnets are equally spaced around a major circumference 1.52 m in diameter, and are mounted with the major axis of the torus vertical in a single vacuum tank 2.59 m in diameter. The design value of maximum magnetic field on the magnetic axis (3.0 teslas) has been reached and exceeded. A maximum magnetic field of 3.23 teslas has been held for a period of 60 minutes, and the coils have not gone normal. When the coils were charged to a maximum magnetic field of 3.35 teslas, the coil system was driven normal without damage to the facility.

INTRODUCTION

The facilities described in this report were built to explore some of the problems of plasma heating and confinement.[1] The scope of this paper is restricted to data on the mechanical, electrical, cryogenic, and magnetic design and performance of the two magnet facilities discussed.

Retrospective Summary of Pilot Rig Performance

The two-coil superconducting pilot rig, which preceded the NASA Lewis bumpy torus, consists of two 18 cm i.d. superconducting coils, each of which can generate 2.0 teslas on their axes.[2] This pilot rig first went into service on December 2, 1964. In the period of 7 years ending December 31, 1971, this pilot rig experienced 584 liquid helium loadings, 550 experimental runs with the magnets charged, and 113 coil normalcies. As of January 1, 1972, the facility continued to operate satisfactorily and without degradation of the coil performance.

While the performance of the coils has not degraded, some subsystems associated with the pilot rig facility have failed over the 7-year period of operation. The pilot rig initially had upper and lower liquid level sensors in both canisters of both dewars. These eight liquid level sensors (four for helium, four for nitrogen) consisted of 1/10 watt carbon resistors connected to a commercial readout box. Drift from the initial calibration of these carbon resistors occurred during the first few months of facility operation. The first carbon resistor failed approximately 6 months after initial operation and the final resistor failed approximately

5 1/2 years after initial operation.

The superconducting coils were initially equipped with persistent current switches, which consisted of 10 mil NbZr wire wrapped around a 2-watt carbon resistor. These persistent current switches operated satisfactorily until 2 1/2 years after the facility went into service. At that time, the carbon resistor on one of the two coils failed, which made it impossible to charge up the coil to which it was attached. The second persistent switch continues to operate satisfactorily at the present time.

A third subsystem failure occurred approximately 4 1/2 years after the coils went into service, when the coil-to-ground insulation failed in one of the two coils. Because the facility is still operational, the failure mode of the coil-to-ground insulation, and the failure mode of the liquid level sensors have not yet been ascertained.

Design Goals of the NASA-Lewis Bumpy Torus

It has been proposed to employ the bumpy torus concept for plasma confinement, utilizing 12 superconducting magnetic field coils arranged end-to-end in a toroidal array.[3] The ions which, in a linear magnet array, would be lost to the vacuum tank wall are constrained by the magnetic field to circulate around the major circumference of the torus. The number of field coils, the major and minor diameters of the toroidal array, and the design magnetic field strength were the result of an economic optimization.[4] The major characteristics of the bumpy torus geometry are listed in Table I, and result from maximizing the volume of confined plasma per dollar, subject to the constraint of adiabatic confinement of 10 keV deuterium ions.

FACILITY DESIGN

Superconducting Coil Design

The characteristics of the coil windings are shown in figure 1. This coil design was arrived at with the assistance of members of the Magnetics and Cryophysics Branch of the Electromagnetic Propulsion Division at the Lewis Research Center.[5,6] At the time the coils were designed, surplus 80 mil (2.03 mm) square, untwisted, NbTi superconducting wire was available. This material had approximately 14 strands of superconducting material with a copper to superconductor ratio of 3.07. Seven of the 12 coils were wound with the square superconducting wire, and 5 of the 12 coils were wound with round, twisted superconducting wire. This round wire has approximately 133 strands of NbTi superconducting wire embedded in a copper matrix with a copper to superconductor ratio of 2.5:1. The diameter of this wire is 85 mils (2.16 mm), and the wire is coated

with a layer of insulating oxide.

The configuration of the cooling passages and the relation of the windings to the spoolpiece is shown on figure 1. The windings are not drawn to scale. The windings consist of 18 layers with approximately 54 turns per layer. The individual turns of a given layer of the square wire are spaced apart by intermittent tabs of mylar tape, which adheres to one face of the square wire. The mylar tape tabs are 2.03 mm wide, approximately 12.7 mm long, and are spaced approximately 6.3 mm apart. The radial passageways formed by adjacent turns on a given layer allow liquid helium to penetrate the windings radially to irrigate the individual wires. There are no tabs between individual turns of the round wire. Radial flow of liquid helium also occurs through radial slots in the G-10 glass epoxy material which insulates the windings from the spoolpieces. This material is alternately slotted on both sides, and holes are drilled through the slots to permit liquid helium to penetrate inner layers of the winding. The liquid helium also irrigates the upper and lower surfaces of each layer of wire through cooling passages formed by diagonal strips of .38 mm thick G-10 insulating material.

As indicated in figure 1, each of the 12 coils has a shunt in parallel with the coil, which serves to dissipate the stored magnetic energy in the event of a coil normalcy. These shunts consist of a type 304 stainless steel strip approximately 11.4 cm wide, 160 cm long, and 0.46 mm thick. These stainless steel strips were insulated on both sides with mylar tape, and then rolled into the configuration shown in figure 1.

The magnetic field resulting from the 12 coils was calculated by a computer program which summed the contribution of all 12 coils in the final assembly. Figure 2 shows a plan view of the magnetic field strength contours in the equatorial plane of the torus.

Mechanical Design and Configuration of Facility

The superconducting winding discussed in the previous section was wound on a spoolpiece, the dimensions of which are given on the isometric drawing of figure 1. The sheet metal forming the outer circumference of the canisters was welded circumferentially to the edges of the spoolpieces. The magnetic forces acting between adjacent coils are borne by four spacer bars. These spacer bars were fabricated in three pieces, in order to facilitate their assembly after the coils were mounted in place. At one end of each spacer bar is a turnbuckle assembly which permits adjustment of the spacing between adjacent coils.

Figure 3 shows a photograph of three coils in various stages of fabrication. On the right-hand side is a coil without its outer shell in place. The center coil has the liquid helium canister cover welded in place, and the left-hand coil has the liquid nitrogen temperature shield mounted around the liquid helium temperature canister. In between the coils are the spacer bars. Several of

the spacer bars are covered by liquid nitrogen heat shields. Also evident in figure 3 is the manner in which the coils are mounted to the upper helium manifold. This manifold is 6.3 mm in outside diameter and consists of stainless steel tubing with a wall thickness of 5.1 mm. The weight of the 12 coils is borne by tabs which are welded to the upper liquid helium manifold. This manifold is suspended from a yoke which is attached to the liquid helium reservoir. There are three of these liquid helium reservoirs, each of which has a capacity of 100 liters.

Figure 4 shows an isometric cutaway drawing of the entire magnet facility. The drawing shows the 12 anode rings, which generate the plasma, located midway between the 12 magnets. The venting helium gas rises through the upper connection to the coil canisters, through the upper liquid helium vent manifold, and through a standpipe to the top of the three liquid helium reservoirs. The vented gas travels along the top of the reservoirs and out vent lines located at two stations in the vacuum tank. One of the helium vent lines also contains the coil power leads and the coil sensor leads, both of which are cooled by the venting helium gas.

Cryogenic System Design

A schematic of the helium flow system is shown in figure 5. The 12 superconducting coils are connected in parallel across the upper and lower liquid helium manifolds. If it is desired to refill the system while the magnets are charged up, liquid helium can be fed directly into the reservoirs.

An innovation in this facility is the use of 1" A&N fittings at liquid helium temperatures and in a vacuum environment. Altogether this magnet facility contains 36 A&N fittings at liquid helium temperatures, and it also contains 24 stainless steel bellows between the coils and the upper and lower liquid helium manifolds. On figure 6 is shown a 1" A&N fitting which was used successfully at liquid helium temperatures. Special precautions must be taken to prevent leaks from developing when such A&N fittings are used at liquid helium temperatures and in a vacuum environment. These precautions included coating both mating surfaces with liquid teflon, allowing the liquid teflon to dry, and applying a torque to the fittings of at least 100 ft-lbs (135 N-m).

On figure 7 is shown a schematic drawing of the liquid nitrogen flow system in this facility. The liquid nitrogen flows continuously through the system, and consists of seven separate and parallel flow paths. Two liquid nitrogen circuits each cool the inner bores of six of the liquid nitrogen can covers. These carry away the radiant heat loading due to the plasma. There are two liquid nitrogen circuits, (each including six coils) which snake around the remainder of the liquid nitrogen coil covers and remove the radiant heat load. Separate liquid nitrogen circuits cool the radiation shields around the three liquid helium reservoir tanks.

The liquid nitrogen can covers on each coil contain eight A&N fittings, which are used to make the connections of the coil covers to the manifolds. Each of the four lines connecting the two liquid nitrogen circuits to their manifolds contain a stainless steel bellows to permit final fitting of the coil in position.

Vacuum System Design

The vacuum tank is evacuated by a 300 CFM (141 l/s) mechanical forepump, which is connected to a 32 in. (81 cm) oil diffusion pump with a rated pumping speed of 32,000 l/s. The diffusion pump is filled with silicone 705 oil, and has a liquid nitrogen cold baffle to prevent back-streaming of the diffusion pump oil into the vacuum tank. Between the vacuum tank and the liquid nitrogen baffle is a venetian blind-like pumping speed controller, which permits independent variation of the background pressure and pumping speed.

The vacuum tank is constructed of type 304 alloy stainless steel and is nonmagnetic. All of the fixtures and fittings of the magnet assembly are of stainless steel or of nonmagnetic material to avoid perturbing the magnetic field. The vacuum tank is 2.59 m inside diameter, and contains 12 15.2-cm diameter ports equally spaced around a 152 cm diameter circle on the bottom of the vacuum tank. These ports are in the midplane of the plasma volume between each of the 12 magnetic field coils. Also providing access to the experimental volume are 12 25.4-cm diameter ports around the circumference of the vacuum tank. These ports, with axes in the major plane of the torus, permit visual and experimental access to the plasma volume. Two of them are canted at an angle to permit tangential access to the toroidal plasma in both clockwise and counterclockwise directions. The lid of the vacuum tank is removable and contains 12 20.3-cm diameter flanges through which the 12 anode rings are inserted. In addition to these 36 ports, there are six additional ports for the liquid helium transfer line, for the liquid nitrogen and liquid helium vent, and for other service lines.

Instrumentation and Electrical Design

Liquid helium level sensors are installed at the bottom and top of the liquid helium cans of all 12 coils. There are eight liquid level sensors at equally spaced intervals in the three liquid helium reservoir tanks. Altogether there are liquid helium sensors in 48 different locations throughout the system. Each one of these 48 positions has a redundant spare.

The 12 coils are wired in series, with only two leads connecting the coil assembly to the power supply outside the liquid helium environment. The voltage drop across each of the 12 coils is monitored by leads attached to the coil. The 12 coils are connected by 10-cm long lap splices in the superconducting wire. Figure 8 is a sketch of the magnet leads and the manner of their connection from the coils to the terminals on the magnet lead termination box.

FACILITY PERFORMANCE

Superconducting Coil Performance

Each of the coils was individually tested and met or exceeded its designed current of 700 A before being incorporated in the facility. These coils were each charged at rates that ranged from 75 A/min up to 180 A/min. The departure from field uniformity, attributable to variations in the number of ampere turns per coil, should be less than ±0.3 percent in this array of 12 coils. The individual coils produced 41.1 G/A (0.00411 T/A) on the magnetic axis at the coil midplane, and 47.8 G/A (0.00478 T/A) at the same location for the entire coil array.

The result of testing the superconducting coil performance for the entire array was that the maximum magnetic field on the magnetic axis could be held at 3.23 T for at least 60 minutes, which compared with the design magnetic field of 3.0 T. When the coils go normal, it takes approximately 60 seconds for the energy of the magnetic field to dissipate and the coil current to go to zero. It was found that this facility would achieve its design maximum magnetic field of 3.0 T over charging rates from 60 A/min up to 180 A/min.

Mechanical Performance

In order to test the mechanical and cryogenic design of the facility, a coil pair test was performed in another vacuum tank. The two coils, canted at an angle of $30°$, have the maximum possible compressive forces acting between them and hence provide a worst possible test case of the spacer bars and the other structural elements of the coil assembly. These two coils were energized up to a current of 800 A and were able to hold at this current. No form of mechanical failure resulted from this test. The A&N fittings did not leak during this test.

Performance of Cryogenic System

The liquid helium system and the coils were cooled from room temperature to liquid nitrogen temperatures by evacuating the large vacuum tank, flowing liquid nitrogen to the heat shields. The temperature of the liquid helium system was monitored with thermocouples at several locations. When the system was sufficiently cooled by radiative heat transfer from the liquid nitrogen shields, the liquid helium system was further reduced in temperature by passing cold helium gas through the system from the mobile liquid helium dewar outside the building. Liquid helium was then permitted to flow into the liquid helium system to cool the system the remaining increment to liquid helium temperatures.

The backpressure in the system was measured during a coil normalcy which took place at maximum magnetic field of 3.0 T. It was found that the pressure at the top of the liquid helium reservoirs was less than 2.4 lb/in.^{2} absolute (1.7×10^4 N/m^2), and it appeared that approximately 110 liters of liquid helium were boiled off during the process. When one coil in the system went normal first, this

triggered from one to six additional coils to go
normal. No damage to the coils occurred as a result
of the coil normalcies.

Performance of Instrumentation and Electrical Systems

The liquid helium sensors performed satisfac-
torily. However, of the 96 liquid helium level
sensors, it was found that five were open-
circuited immediately before the system was cooled
down to cryogenic temperatures for the first time.
These open circuits may have resulted from mechani-
cal shock and vibration during transport or assembly.
The performance of the coil power supply was quite
satisfactory. It ramped up to the rated field and
down automatically, and produced no unanticipated
behavior during the coil charging process.

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2. J. R. Roth, D. C. Freeman, Jr., and D. A. Haid,
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   van Leeuwen Theorem," NASA TN D-3880, April
   1967.

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   Mirror Fields for Controlled Fusion Research,"
   NASA TM X-1251, July 1966.

5. W. D. Coles, J. C. Laurence, and G. V. Brown,
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6. J. C. Laurence, "Superconductive Magnets,"
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   Symposium, Washington, D.C., March 23-24, 1970,
   J. S. Blizin, Editor, pp. 182-200.

TABLE I

DESIGN CHARACTERISTICS OF THE
NASA-LEWIS BUMPY TORUS FACILITY

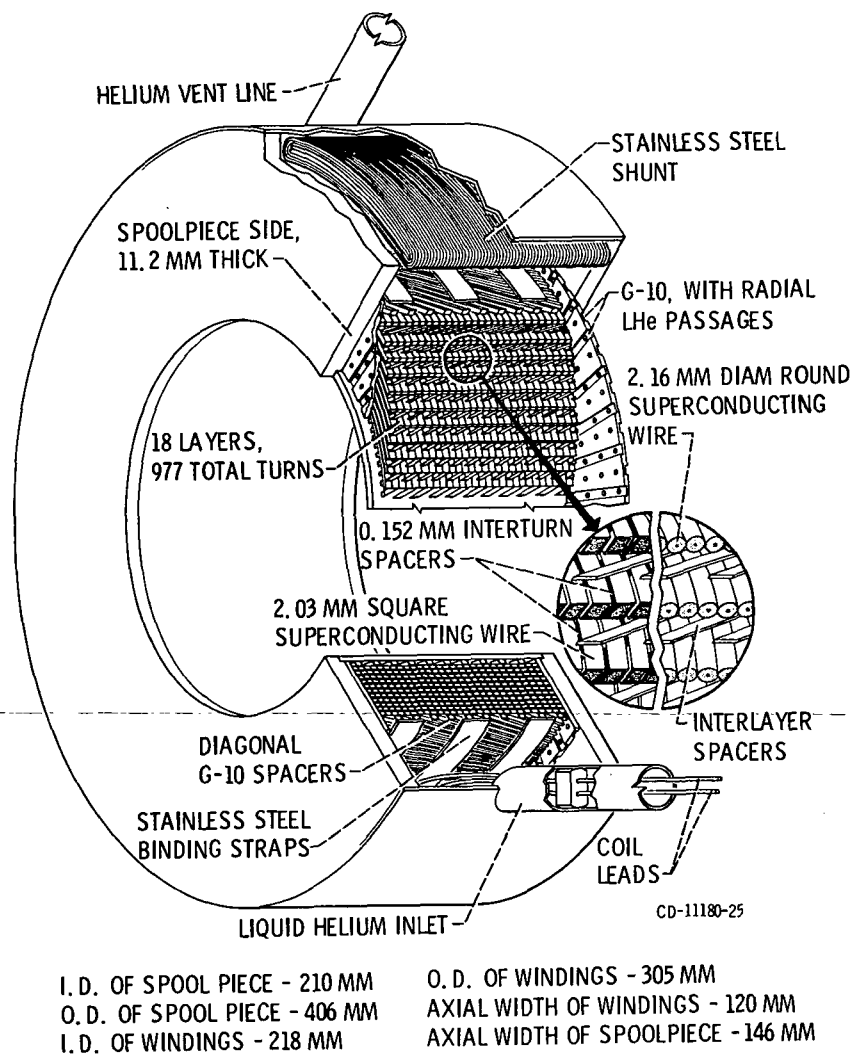|	
Major diameter of torus	1.52 m
Inside diameter of spoolpiece	21.0 cm
Axial width of coil windings	12.0 cm
Inside diameter of coil winding	21.8 cm
Outside diameter of coil winding	30.5 cm
Designed coil current	700 A
Maximum magnetic field on axis of a single coil at 700 A	3.0 T
Mirror ratio of major circumference	2.48:1
Maximum magnetic field on magnetic axis of entire toroidal array	3.0 T

HELIUM VENT LINE

STAINLESS STEEL SHUNT

SPOOLPIECE SIDE, 11.2 MM THICK

G-10, WITH RADIAL LHe PASSAGES

2.16 MM DIAM ROUND SUPERCONDUCTING WIRE

18 LAYERS, 977 TOTAL TURNS

0.152 MM INTERTURN SPACERS

2.03 MM SQUARE SUPERCONDUCTING WIRE

INTERLAYER SPACERS

DIAGONAL G-10 SPACERS

STAINLESS STEEL BINDING STRAPS

COIL LEADS

LIQUID HELIUM INLET

CD-11180-25

I.D. OF SPOOL PIECE - 210 MM   O.D. OF WINDINGS - 305 MM
O.D. OF SPOOL PIECE - 406 MM   AXIAL WIDTH OF WINDINGS - 120 MM
I.D. OF WINDINGS - 218 MM   AXIAL WIDTH OF SPOOLPIECE - 146 MM

Figure 1. - Isometric cutaway drawing of a superconducting coil. The insert shows the details of the cooling passages in the round and square wire coils.
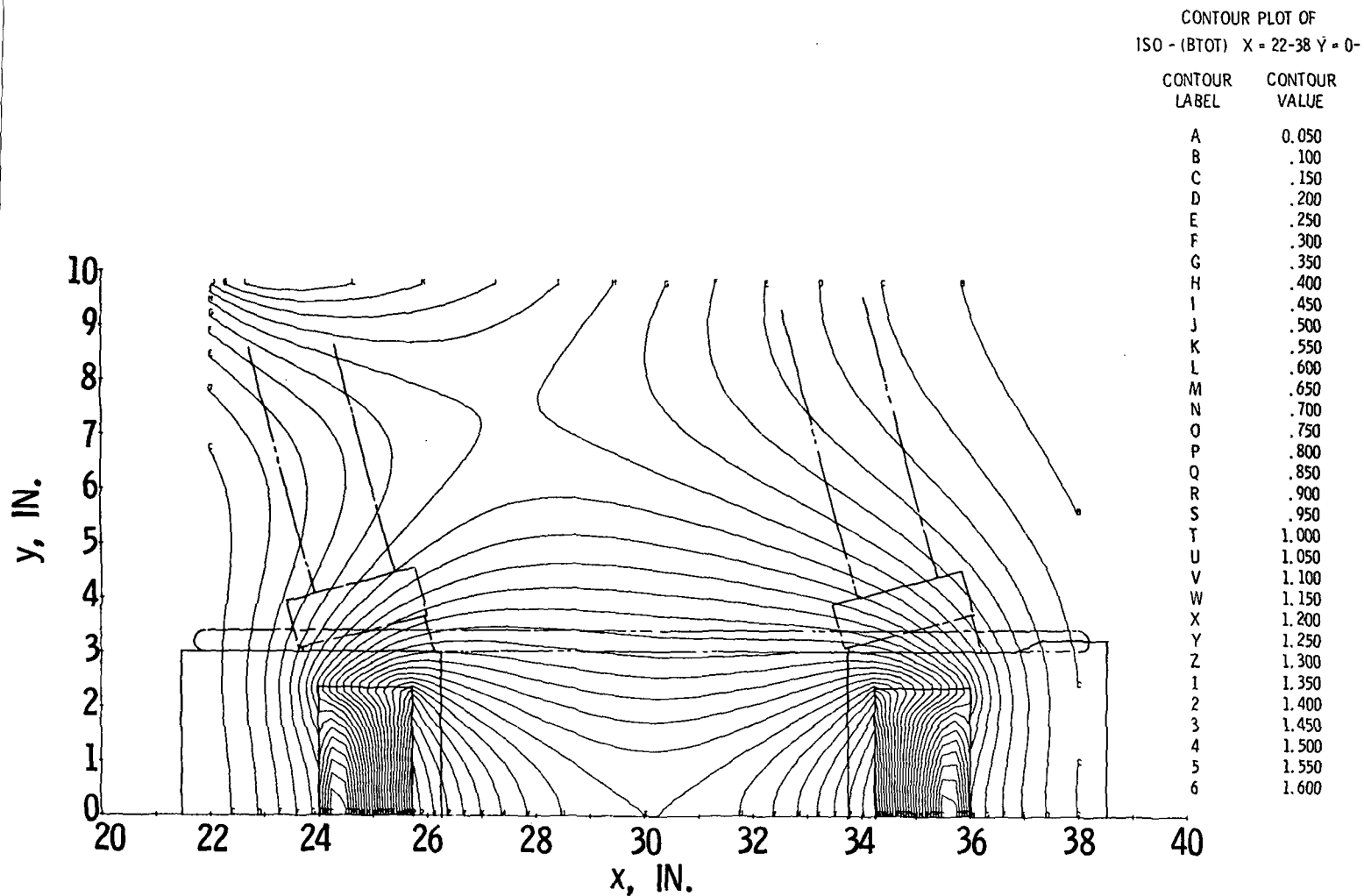
Figure 2. - Contours of magnetic field strength in the plane of the torus. The magnetic field on the axis at the coil midplane is normalized to unity.
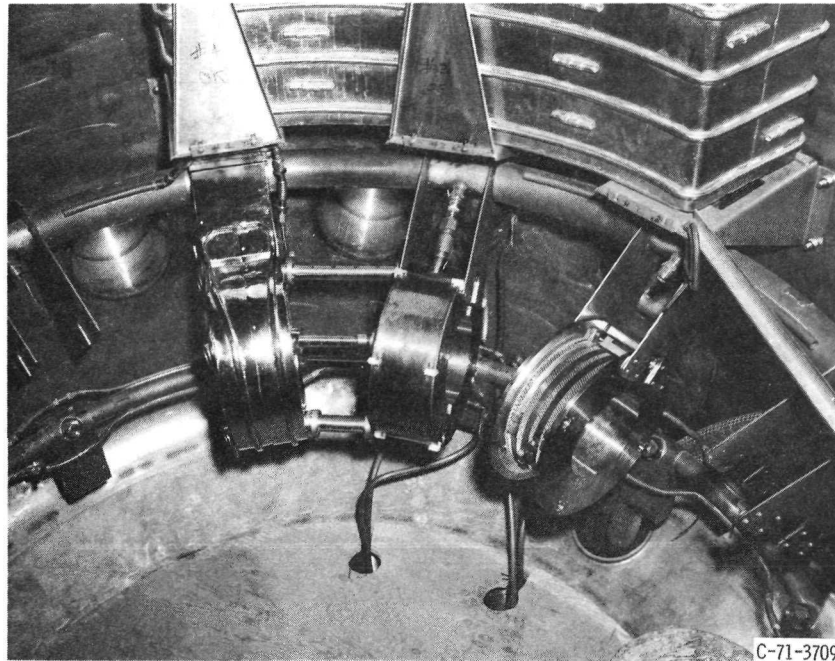
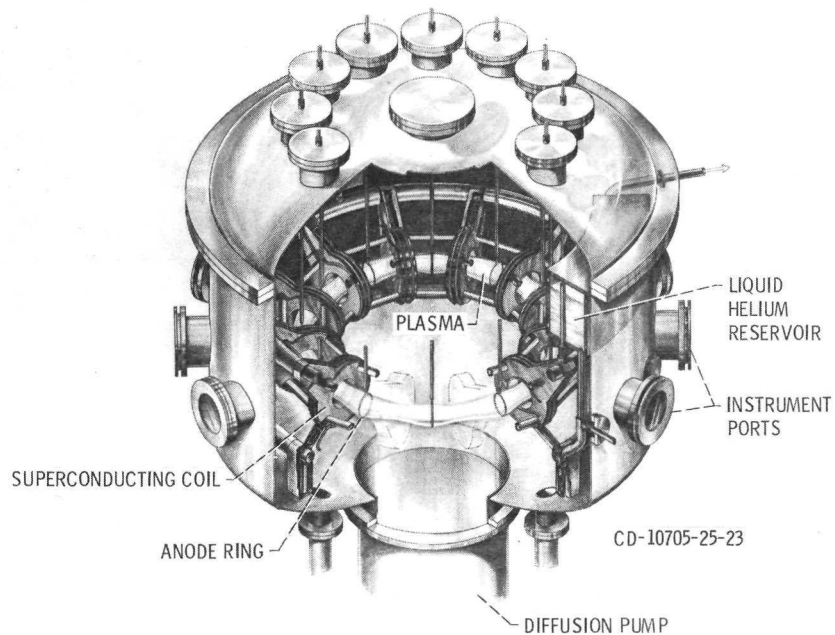Figure 3. - Photograph of three coils in various stages of assembly.

Figure 4. - An artist's isometric cutaway view of the entire magnet facility. Note the anode rings located halfway between each coil, the liquid nitrogen covers over the liquid helium system, and the three liquid helium reservoirs.
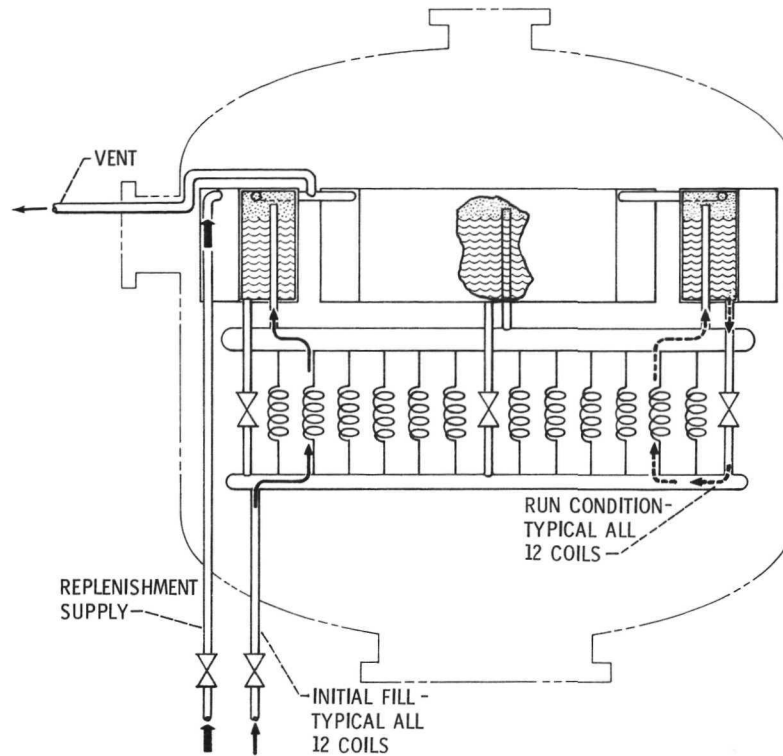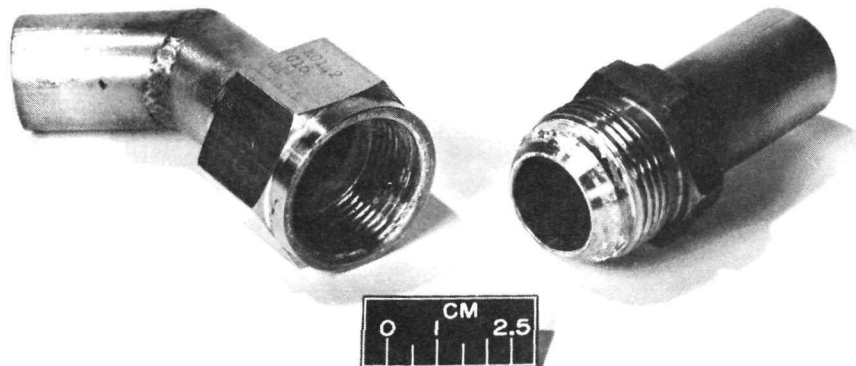
Figure 5. – A schematic drawing of the liquid helium flow system. The two
modes of operation indicated are for initial filling with liquid helium, and
for filling while the magnets are fully charged.

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Figure 6. – A photograph of a 1-in. A&N fitting taken from the coil pair test
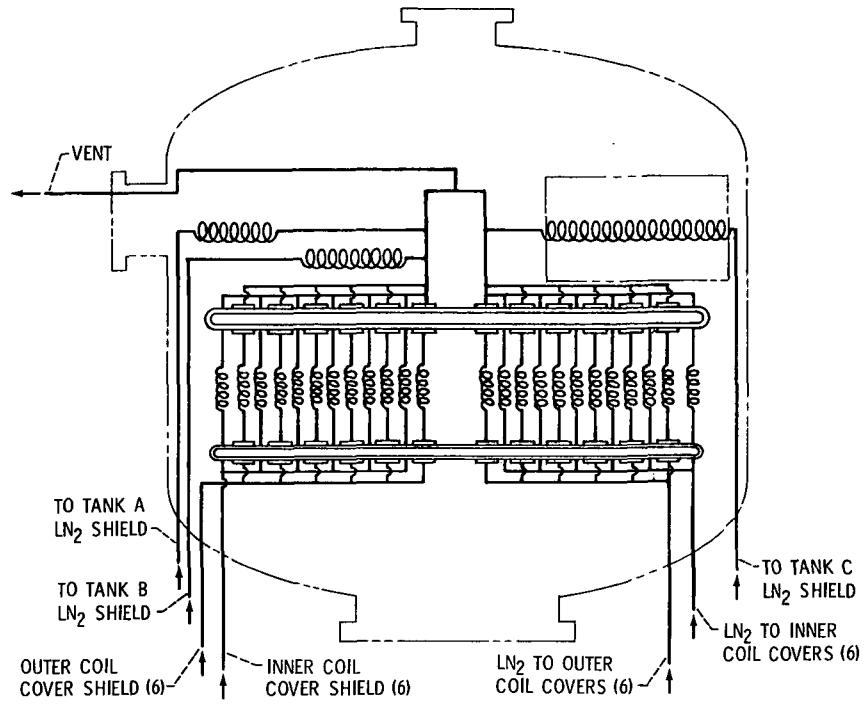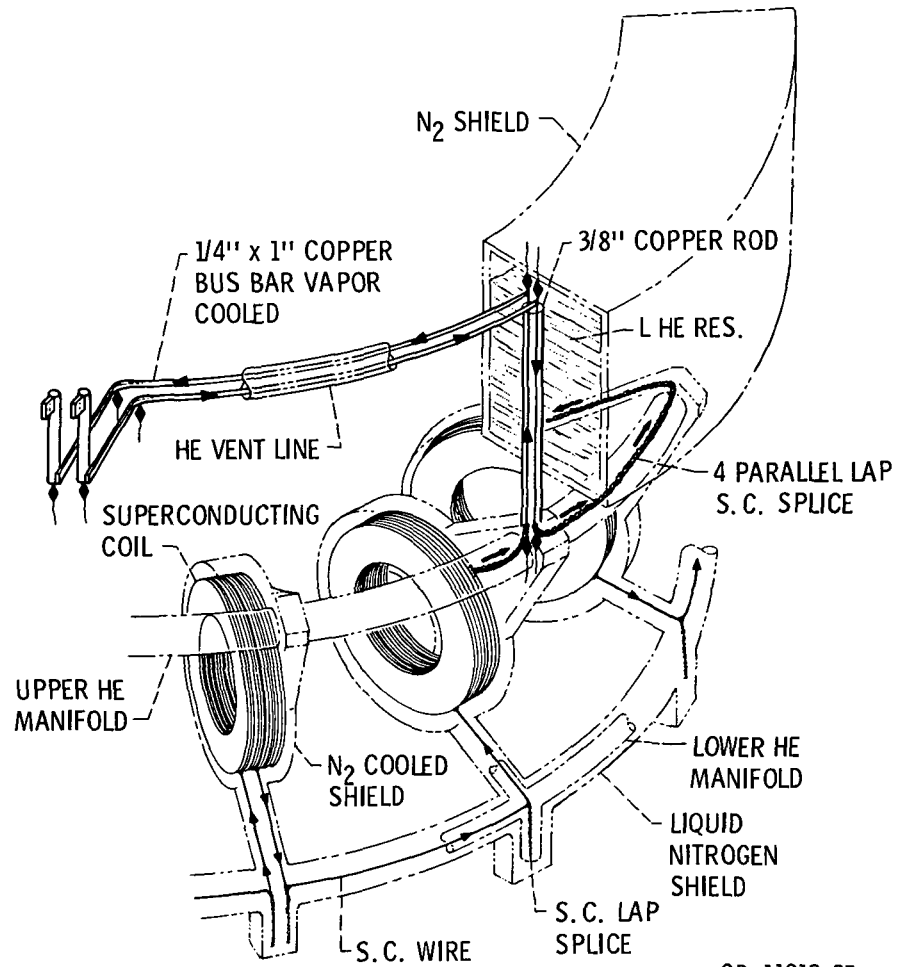apparatus. These fittings consisted of stainless steel mating on stainless
steel.

Figure 7. – Schematic drawing of the liquid nitrogen flow system.

N$_2$ SHIELD

1/4" x 1" COPPER BUS BAR VAPOR COOLED

3/8" COPPER ROD

L HE RES.

HE VENT LINE

4 PARALLEL LAP S. C. SPLICE

SUPERCONDUCTING COIL

UPPER HE MANIFOLD

N$_2$ COOLED SHIELD

LOWER HE MANIFOLD

LIQUID NITROGEN SHIELD

S. C. LAP SPLICE

S.C. WIRE

CD-11212-25

Figure 8. - Sketch of the magnet leads and the method of their connection from the coils to the room temperature terminals.